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On the origin of M81 group extended dust emission

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ABSTRACT

Galactic cirrus emission at far-infrared wavelengths affects many extragalactic observations. Separating this emission from that associated with extragalactic objects is both important and difficult. In this paper we discuss a particular case, the M81 group, and the identification of diffuse structures prominent in the infrared, but also detected at optical wavelengths. The origin of these structures has previously been controversial, ranging from them being the

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result of a past interaction between M81 and M82 or due to more local Galactic emission. We show that over an order of a few arcmin scales, the far-infrared (*Herschel* 250 μm) emission correlates spatially very well with a particular narrow-velocity ($2\text{--}3\text{ km s}^{-1}$) component of the Galactic H I. We find no evidence that any of the far-infrared emission associated with these features actually originates in the M81 group. Thus we infer that the associated diffuse optical emission must be due to galactic light-back scattered off dust in our galaxy. Ultraviolet observations pick out young stellar associations around M81, but no detectable far-infrared emission. We consider in detail one of the Galactic cirrus features, finding that the far-infrared H I relation breaks down below arcmin scales and that at smaller scales there can be quite large dust-temperature variations.

Key words: dust, extinction – galaxies: evolution – galaxies: individual: M81.

1 INTRODUCTION

It is clear that galaxy–galaxy interactions play a major role in the evolution of primordial gas clouds into the spectacular galaxies we see today. Particularly important and striking interactions occur when the speed of interaction is well matched to the internal velocities of the stars and gas. Thus small galaxy groups can potentially provide just the environment for dramatic gravitational disturbance. Beyond the Local Group the closest example of this is in the environment around M81. The M81 group lies at a distance of about 3.6 Mpc (Karachentsev et al. 2004) with radial velocities ranging from -34 km s^{-1} for M81 to 203 km s^{-1} for M82 (Chynoweth et al. 2008), thus tidal disruption is highly likely.

Living up to expectations M81 is known to be surrounded by debris which has previously been best delineated by its emission at 21 cm (Yun, Ho & Lo 1994), although diffuse emission at wavelengths from the optical to the far-infrared can also be readily detected. Previously others have explicitly described the diffuse optical emission from between M81 and M82 as arising from stars either deposited there during a M81/M82 collision or subsequently formed in the gas that was stripped during this event (Sun et al. 2005). Additional support for this comes from a number of recent studies that have identified individual stars way beyond the discs of the individual galaxies involved (Davidge 2008; de Mello et al. 2008; Williams et al. 2009; Mouhcine & Ibata 2010). Contrary to this, a study by Sollima et al. (2010) concludes that these stars can only represent a small fraction of the optical emission with the majority of the light being due to back scattering from foreground dust in our Galaxy, dust associated with 21-cm cirrus emission. By looking at various far-infrared luminosity ratios Sollima et al. also conclude that the majority of the far-infrared emission is not associated with M81 but is again from Galactic cirrus.

Deciding on this issue is not a new problem. The area of sky around M81 has long been known for diffuse emission at optical wavelengths. Sandage (1976) describes it as ‘high-latitude reflection nebulae illuminated by the Galactic plane’. Arp (1965) describes faint diffuse emission that he assigns to the M81 group and one of the most prominent features has become known as ‘Arp’s loop’ (see Fig. 1). So the origin of this emission has been somewhat controversial for many years. Our attention was drawn to this problem because recent wide field *Spitzer* and *Herschel* data of other regions of the sky show extended filamentary structures that are best explained by thermal emission from dust above the plane of our Galaxy, i.e. the Galactic cirrus whose large-scale structure was first defined at lower resolution by *IRAS*. The emission looping around and apparently connected to M81 appears very similar in shape to

this cirrus emission, yet one might also expect structures just like this within a galaxy group. To shed new light on this problem we compare *Herschel* high-resolution far-infrared observations with high-spatial and velocity resolution 21-cm data.

2 DEBRIS OR CIRRUS?

We will use two primary data sources to help us decide on the debris or cirrus issue: *Herschel* space telescope Photodetector Array Camera and Spectrometer (PACS) 160 μm (Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) 250-, 350- and 500- μm science demonstration scan map data and The H I Nearby Galaxy Survey (THINGS) Very Large Array (VLA) data (Walter et al. 2008).

PACS observations were performed as four pairs of orthogonal scans covering an area of $\sim 40 \times 40\text{ arcmin}^2$ with a scan rate of 20 arcsec s^{-1} . The SPIRE observations consist of two repetitions of cross-linked scans over approximately the same area with a nominal scan speed of 30 arcsec s^{-1} . The reduction of both the PACS and SPIRE data is described in Bendo et al. (2010) and references therein. The final rms of the images are $\sim 3, 12, 12$ and 13 mJy beam^{-1} at 160, 250, 350 and 500 μm . The full width at half-maximum of the beams are $\sim 11, 18, 25$ and 37 arcsec at 160, 250, 350 and 500 μm , respectively. There is a calibration uncertainty of ~ 15 per cent (Swinyard et al. 2010). M81 was observed by the THINGS project using the VLA (Walter et al. 2008). They have produced a 21-cm data cube with a noise of $\sim 0.7\text{ mJy beam}^{-1}$, a spatial resolution of 12.5 arcsec and a velocity channel width of 2.6 km s^{-1} .

Extended filamentary structures external to the disc of M81 are clearly seen in emission in all of the *Herschel* bands. In Fig. 1 (top panel) we illustrate this with the 250- μm data, four particularly bright regions are indicated by the red boxes. These same structures can also be clearly seen in the *Spitzer* (Multiband Imaging Photometer for SIRTf, MIPS) 24-, 70- and 160- μm data (Sollima et al. 2010), so there is emission over a wide range of far-infrared wavelengths.

If this material is associated with M81 group tidal debris then it must consist of relatively large quantities of dust, and there must be a source of heating either from stars within the dust, also accounting for the optical emission, or from stars further away in M81. Alternatively if it is Galactic cirrus, then dust can account for all of the ultraviolet (UV), optical and infrared emission. In the optical, it would be scattered light from the disc of our Galaxy and in the infrared thermal emission. We also have a deep optical Sloan Digital Sky Survey (SDSS) image that clearly shows diffuse emission that

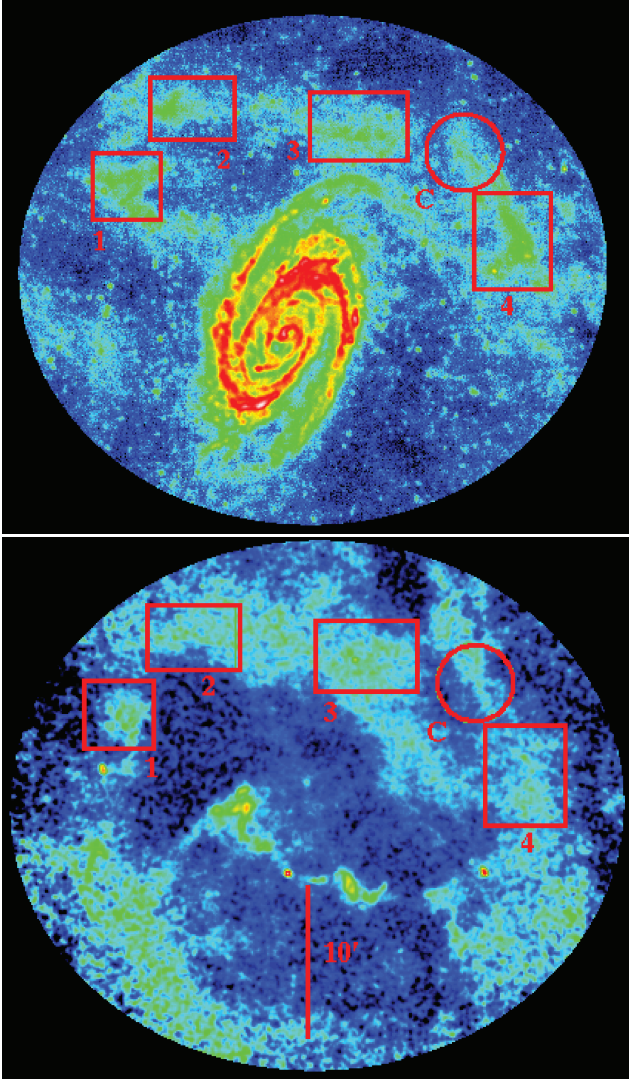


Figure 1. Top panel: the SPIRE 250- μm data. Of particular interest is the extended emission to the north of M81, four particularly bright regions are highlighted by boxes 1–4. Arp’s loop extends from M81 to boxes 1, 2 and then 3. A possible star formation region is highlighted by the circle and labelled C. Bottom panel: this is channel 75 from the THINGS M81 H I data cube which is centred at -1.2 km s^{-1} . The H I emission corresponds very well with the extended 250- μm emission, again highlighted by the same boxes. A size of 10 arcmin $\approx 10.5 \text{ kpc}$ at the distance of M81 is marked by the vertical line. North is towards the top and east is towards the left-hand side.

is spatially correlated with the far-infrared (see Section 4). Given that there is normally a correlation between Galactic cirrus gas and dust (Boulanger et al. 1996), the 21-cm data may be useful in deciding this issue because in principle we can select the cirrus gas via its velocity. We have smoothed the THINGS 21-cm data to the spatial resolution of the SPIRE 250- μm data, re-gridded to the same pixel scale and then considered the spatial correlation of the 21-cm and 250- μm data. The published THINGS moment zero map, which is the sum of 21-cm emission over $\sim 250 \text{ km s}^{-1}$ does not correlate particularly well with the diffuse far-infrared emission (see below), but that is not true of the individual channel maps. The problem with M81 is that because of its relatively low velocity, its H I is mixed with that of the Galaxy and separating the two is not without ambiguity. M81 can be traced throughout the THINGS 21-cm chan-

nel maps, but at velocities around zero a number of other striking and extended structures appear with very narrow velocity widths. For example Fig. 1 (bottom panel) shows the H I single channel map centred at a velocity of -1.2 km s^{-1} , the structures seen in this image are almost completely contained within this one channel of velocity width 2.6 km s^{-1} and disappear completely two channels away. What is striking is the correspondence of the H I emission in this narrow velocity range with the 250- μm emission. If at the distance of M81, the H I structures would have to sustain an almost constant line-of-sight velocity over a distance of more than 30 kpc. This does not seem possible for what in this case would almost certainly be a tidal feature, which more typically have a velocity range of hundreds of km s^{-1} (Minchin et al. 2007). On the other hand, if it is cirrus above the plane of our Galaxy (distance at most 1 kpc?), then the feature has a length of only about 9 pc and its almost constant line-of-sight velocity is more understandable. In fact small velocity widths seem to be a characteristic of low-velocity hydrogen clouds above the plane of our galaxy, these typically have velocity widths of $3\text{--}7 \text{ km s}^{-1}$ (Stanimirovic et al. 2006).

Boulanger et al. (1996) have previously considered the correlation of Galactic H I with far-infrared emission over a wide range of wavelengths (see also Davies et al. 1997). They use COBE (DIRBE) far-infrared and Leiden/Dwingeloo H I data with a spatial resolution of about 40 arcmin to derive a linear relation between the H I column density and the far-infrared emission (Fig. 2). This spatial scale is large compared to the scale of our image, but nevertheless we have considered the relationship between the four regions labelled on Fig. 1 (each only a few arcmin in size), these are marked as crosses on Fig. 2. The scatter in the Boulanger et al. data is about 1 MJy sr^{-1} (see their fig. 1) and we might expect even more scatter when averaging over our smaller regions. With the exception of box 1, to which we will return later, we conclude that the *Herschel* 250- μm and THINGS H I data are consistent with the Boulanger et al. (1996) relation for Galactic cirrus emission.

After smoothing to the 500- μm resolution and re-gridding we can use the 160-, 250-, 350- and 500- μm data to estimate a temperature for the dust using a single-temperature grey body with an emissivity

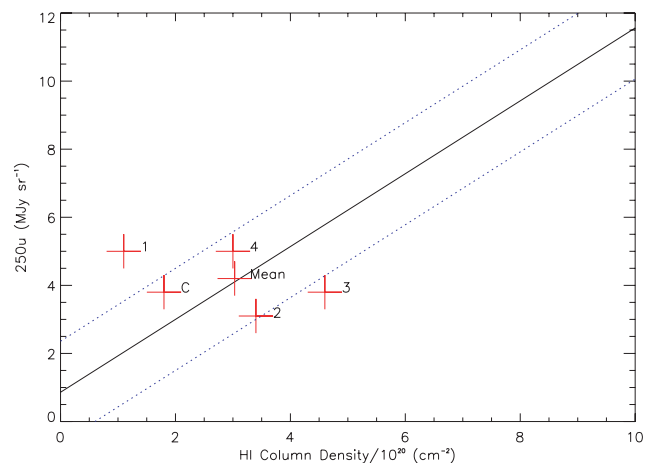


Figure 2. The solid line gives the best fit to the Boulanger et al. (1996) DIRBE 240- μm and Leiden/Dwingeloo H I data of $\text{FIR}_{240}(\text{MJy sr}^{-1}) = 1.07N_{\text{HI}}/10^{20}(\text{cm}^{-2}) + 0.86$, the dotted lines indicate the scatter in the data. The four numbered points are the values for the corresponding rectangular apertures (H I in a single channel) shown on Fig. 1, their mean value is also marked by a red cross. The point marked C is for the circular aperture marked on Fig. 1 which covers the star formation region labelled C on Fig. 3.

that scales as λ^{-2} (Li & Draine 2001). The derived temperatures for regions 1, 2, 3 and 4 are 20, 21, 18 and 21 K, respectively (each with an error of about ± 3 K). Unhelpfully these temperatures are consistent with the temperature of Galactic cirrus, Boulanger et al. (1996) give a mean value of $T \approx 18$ K (see also del Burgo et al. 2003), and with the global dust temperature of M81 (Bendo et al. 2010).

Given the spatial similarities of the far-infrared emission and the Galactic atomic gas, the correspondence of the data with the Galactic far-infrared/HI relation and the similar temperature to Galactic cirrus, we conclude that some substantial fraction of the SPIRE 250- μ m emission has an origin in our galaxy and not in the M81 group.

3 IS THERE ANY EXTENDED EMISSION FROM THE M81 GROUP?

Although it appears that some large fraction of the diffuse far-infrared emission is closely associated with Galactic cirrus there are enough differences between the far-infrared and the H I (discussed further in Section 4) to make us curious about some of the emission features. There are for example other objects in this field that we might have hoped to detect in the far-infrared. There are three dwarf galaxies HoIX, A0952+69 and BK 3N and a large northern arm that is prominent in the H I and UV, but not in the far-infrared. Given that far-infrared and UV emissions are both thought to be good tracers of star formation and that UV emission correlates well with high H I column density (Hibbard et al. 2005) UV and M81 H I data could provide further insight.

In Fig. 3 we show the *Galaxy Evolution Explorer* (GALEX) far-ultraviolet (FUV) data and the THINGS H I data for the same region shown in Fig. 1. The H I data is now summed over the velocity range 15–180 km s⁻¹ to pick out hydrogen in the northern part of the M81 group. Note, this velocity range excludes the Galactic component shown in Fig. 1. The above three dwarf galaxies and the spiral arm are indicated on Fig. 3. All three dwarf galaxies are detected as strong sources in the UV and H I. Although they all appear to have young stars associated with them, none is unambiguously detected at 250 μ m or any of the other far-infrared wavelengths. In fact they all reside in regions where there is a distinct lack of far-infrared emission. Holmberg IX has previously been described as the ‘Nearest Young Galaxy’ (Sabbi et al. 2008). The nature of the stellar populations in BK3N and A0952+69 is less clear, but they are probably similar to that of Holmberg IX (Makarova et al. 2002). We can find no H I measurements for BK3N and A0952+69, but Holmberg IX has a measured H I mass of $3.3 \times 10^8 M_{\odot}$ (Swaters & Balcells 2002). For a typical gas-to-dust ratio of 150 this would place it well above our detection limit of about $10^4 M_{\odot}$ of dust, making it both a low-metallicity and low-dust content galaxy. It has been suggested that all three dwarfs are tidal, having formed from the interaction of M81 and M82 some 10^8 yr ago (Yun, Ho & Lo 1994; Makarova et al. 2002). The dwarfs’ lack of far-infrared emission and low metallicity (de Mello et al. 2008) is surprising if they formed from gas originally in the disc of either M81 or M82.

The region labelled C in Fig. 3 is prominent in both the UV and the M81 atomic hydrogen, it sits at the end of the northern spiral arm. This northern arm is a bit of an enigma because it is not seen in ground-based optical data, though individual stars have been found using *Hubble Space Telescope* (HST) data (Williams et al. 2009). It seems that this is gas that has recently been drawn out of M81 and is only just starting to form stars. Coincident with the UV emission and morphologically very similar to it, there is

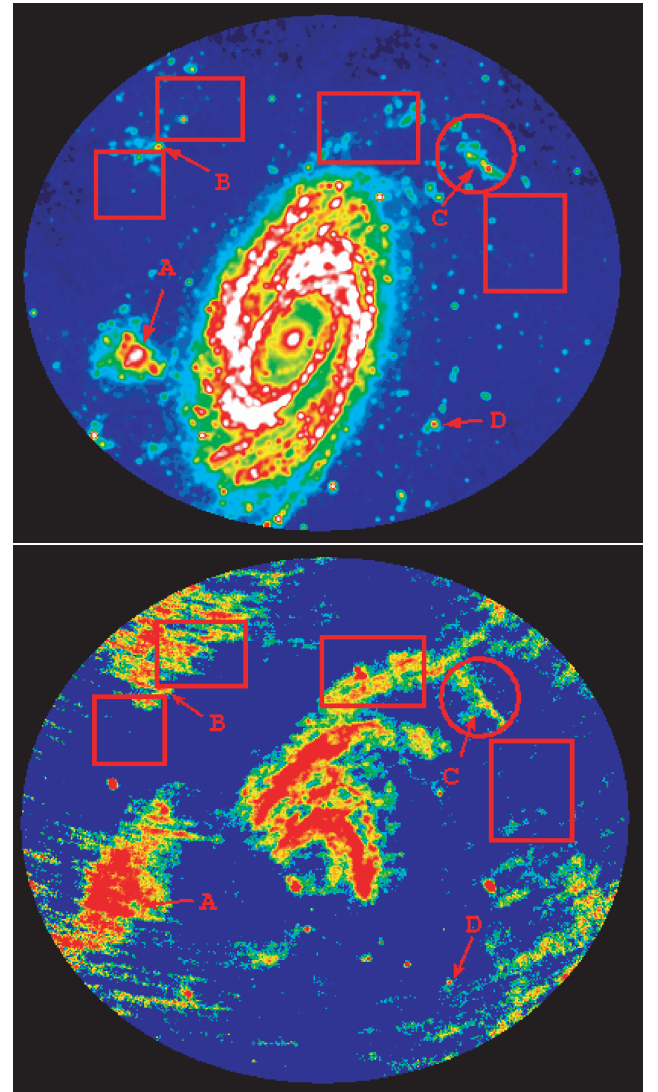


Figure 3. Top panel: the GALEX FUV image of M81. The letters indicate the following: (A) Holmberg IX; (B) A0952+69; (C) northern arm and (D) BK 3N. Bottom panel: THINGS moment zero map summed over 15–180 km s⁻¹. The rectangular boxes are the same as those shown on Fig. 1.

emission in the far-infrared (marked by a circle on Figs 1 and 3). The problem associating this far-infrared emission with M81 is that there also appears to be Galactic cirrus emission in this region – it corresponds to a Galactic H I feature (Fig. 1, bottom panel). If there was far-infrared emission from this obviously active M81 star formation region, then one might expect warmer dust, but its temperature, as derived above for the four other apertures, is 20 ± 3 K, consistent with Galactic cirrus. If we look at the relationship between the 250- μ m emission and the Galactic H I in this area (aperture C in Fig. 1), then it is perfectly consistent with the Galactic cirrus relation (Fig. 2). Similar to the dwarf galaxies discussed above, there is no evidence that this star formation region prominent in both the UV and in atomic hydrogen at the velocity of M81 has any far-infrared emission associated with it.

The H I data (Fig. 1) indicate that a sizeable fraction of the emission from region 1 is actually Galactic cirrus, but this region in particular does not fit the Boulanger et al. (1996) relation very well (Fig. 2) – there is excess far-infrared emission. Recently de Mello

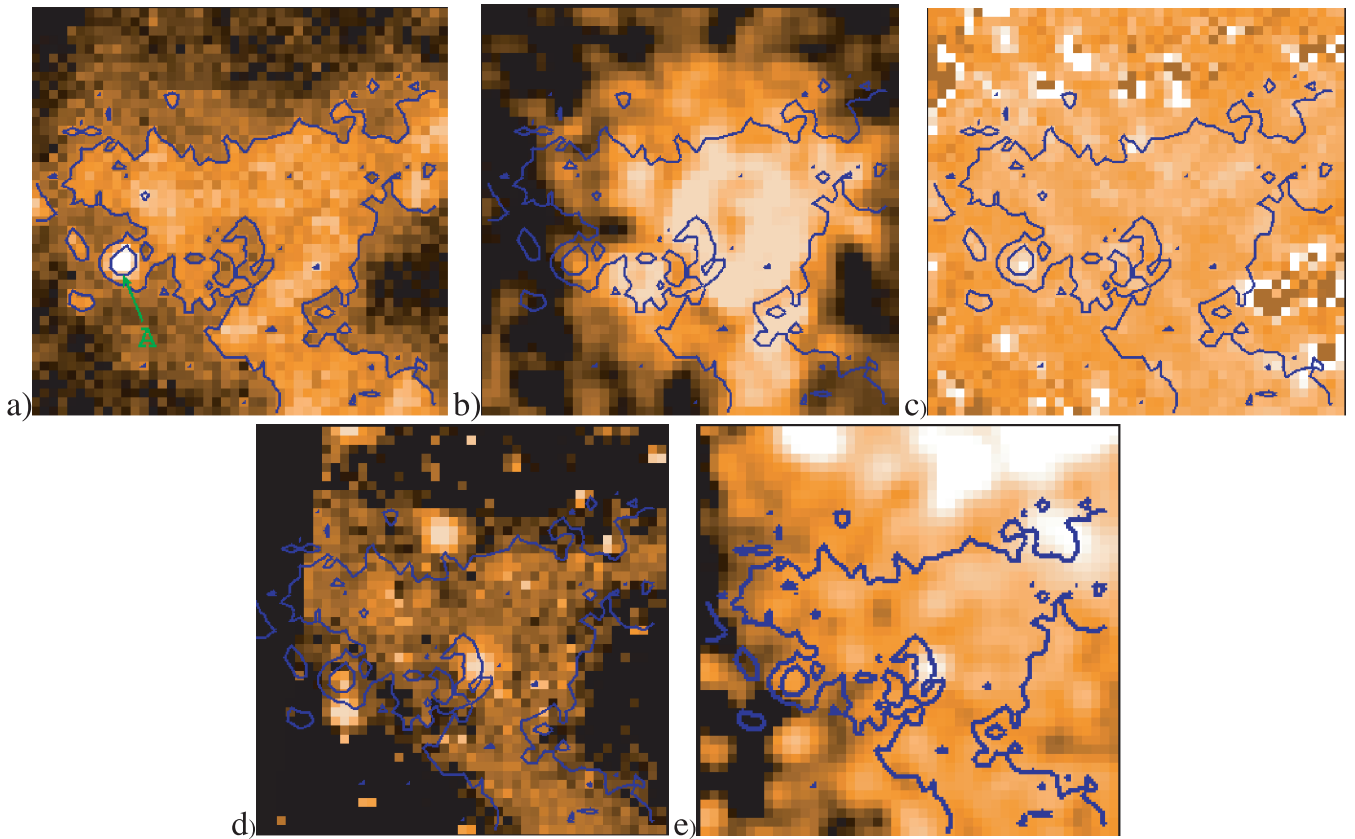


Figure 4. (a) A zoomed-in image of region 1 (250 μm) as defined in Fig. 1. It is approximately an area of $4.5 \times 4.5 \text{ arcmin}^2$. The contours highlight the regions of brightest emission at a level of 5 and 10 MJy sr^{-1} . The brightest source is labelled A. (b) The corresponding 21-cm emission (channel 75, $v = -1.2 \text{ km s}^{-1}$) with the 250- μm contours. (c) The division of the 250- μm image by the 500- μm image with 250- μm contours. (d) SDSS optical data with 250- μm contours. (e) The FUV image. All images are convolved and re-binned to the 250- μm resolution and beam size.

et al. (2008) have used *HST* Advanced Camera for Surveys (ACS) data to search for stars within Arp’s Loop. Their data cover about a third of the northern part of region 1. Surprisingly they find both old ($>1 \text{ Gyr}$) and young ($<10 \text{ Myr}$) stars in the Loop. They suggest that the old stars were actually formed in the disc of M81 or M82 and were drawn out during a tidal passage, while the young stars have formed *in situ*. It is possible that these stars may be a heating source for dust that was also drawn out and so provide an explanation of the excess far-infrared emission from this region compared to expectations for the cirrus. The problem with this explanation is that M81 stars have also been found, using *HST* ACS data, in the northern arm (Davidge 2008; Williams et al. 2009); in fact the detection field lies within box 3 shown in Fig. 1. In this case these stars do not seem to give rise to excess far-infrared emission in box 3. So, the position of point 1 on Fig. 2 may be entirely explained by the inherent scatter in the far-infrared H I relation.

4 A CLOSER LOOK AT THE CIRRUS

Using the *Herschel* and THINGS data we can look at the Galactic cirrus in unprecedented detail (250- μm resolution). Because this is now a study of the interstellar medium within our galaxy, which is really beyond the scope of this paper, we will just make some general comments. We concentrate on region 1, but our conclusions are equally applicable to regions 2, 3 and 4. The size of region 1 is approximately $4.5 \times 4.5 \text{ arcmin}^2$. We do not know the distance to the

cirrus, but if it were at 1 kpc, then 4.5 arcmin would correspond to a little over 1 pc and we are investigating the small-scale structure of the interstellar medium. In Fig. 4(a) we show a more detailed 250- μm image of region 1 with contours that highlight the brighter regions. The brightest region is labelled A.

Fig. 4(b) shows the single-channel H I emission from Fig. 1 with the 250- μm contours overlaid. What is clear is that although there is a good spatial correlation of the far-infrared and H I over scales of the order of 10 arcmin (Fig. 1) and larger (Boulanger et al. 1996), this relation seems to break down at smaller scales. In the fine detail the far-infrared and H I surface brightness distributions look quite different – note the location of object A and the ‘ring’ of higher column density in the H I image. Plotting pixel values of the 250- μm emission against the H I leads to a scatter plot considerably more widely dispersed than the Boulanger et al. relation of Fig. 2. That the relation is better defined at larger scales is illustrated in Fig. 2 where we mark the position of the mean value of all four boxes – it sits almost exactly on the Boulanger et al. relation, which was derived over scales of 40 arcmin. At a level of 3–5 MJy sr^{-1} , it is clear that this ‘cirrus noise’ can be the dominant noise in a far-infrared image. To investigate further the length-scales over which the far-infrared and H I spatially correlate we are investigating their cross-power spectrum. This analysis requires fields that are not dominated by a large nearby galaxy but do have high-resolution H I . Initial results (Liggins et al., in preparation) indicate that the slope of the cross-power spectrum has a break in it consistent with most

of the power of the correlated structures having sizes greater than about 10 arcmin.

Fig. 4(c) shows the 250 μ m/500 μ m colour temperature. The extent of the bright 250- μ m emission is again indicated by the contours. Variations in the colour temperature from pixel to pixel across the cirrus, as bounded by the contours, are large compared to the mean temperature fluctuations between individual regions 1–4. The mean flux ratio is 6.5 ± 1.8 consistent with a temperature of 20 ± 5 K. Similar fluctuations in cirrus temperature, though on half-arcmin scales, have been found by Bot et al. (2009). They conclude that these fluctuations must be due to varying dust properties from region to region and not due to variations in the interstellar radiation field. These small-scale variations in dust properties may then also explain the break down of the far-infrared H I correlation. The bright source A is hotter than average having a flux ratio more than twice the mean value, indicating a temperature of the order of 40 K.

Fig. 4(d) shows a combined SDSS red giant branch (RGB) optical image of the same region. This is the diffuse optical emission, mentioned in Section 1, which Sun et al. (2005) assign to stars in the M81 group. The far-infrared contours illustrate just how well the optical light traces the dust thermal emission, which in turn seems to be associated with Galactic H I. There are individual optical sources, but because of the far-infrared H I association we presume that most of this emission must be back scattered light from stars in the plane of our galaxy. Just south of source A there is a star, but there also seems to be an optical source almost coincident with it. The SDSS galaxy J095751.03+691334.1 matches the position of source A to within a pixel. Object A, with a 250- μ m flux density of 0.1 Jy, is quite plausibly a background source similar to those found in wide area surveys of the sky (Oliver et al. 2010).

Finally, in Fig. 4(e) we show the *GALEX* FUV image. There does not appear to be any correlation between the FUV and the far-infrared over these spatial scales. The emission to the north appears to be associated with A0952+69.

5 CONCLUSIONS

Galactic cirrus emission is prominent in all of the *Herschel* PACS and SPIRE bands making it difficult to unambiguously detect emission from cold diffuse dust in the extragalactic environment. Some previous measurements of the M81 group's diffuse emission over wavelengths ranging from the optical to the far-infrared have underestimated the significant contribution from Galactic cirrus. We find no evidence for extended dust emission from the M81 group, all of the prominent features can be accounted for by Galactic cirrus. An important result is that not all velocity components of the Galactic cirrus gas have dust associated with them, which is maybe a reflection of the different origins of the gas i.e. infalling primordial gas or expelled enriched disc gas. Also the good relationship between cirrus far-infrared emission and H I seems to break down over spatial scales below about 10 arcmin.

Our conclusions provide us with a dilemma at a number of levels. First, the apparent connection of the far-infrared emission with M81, within a galaxy group that has clearly undergone some tidal interaction, makes it very difficult to believe that they are not associated. A particularly nasty astrophysical coincidence! Secondly, given that most of the emission is from Galactic cirrus then what other sources of assumed extragalactic far-infrared emission may actually also be due to cirrus (Cortese et al. 2010)? Thirdly, there are a number of active star-forming regions identified in both the UV and the H I which have no associated far-infrared emission: far-infrared emission is not a good proxy for star formation in these

cases. Fourthly, how can you uniquely distinguish cirrus from extragalactic emission? Our analysis indicates that you need to select a very narrow velocity range for the H I, but even then there is too much scatter in the Boulanger et al. (1996) relation to be very useful unless you are interested in scales greater than about 10 arcmin. This is also true for the variation of far-infrared colours (temperatures) from region to region which can fluctuate considerably over smaller spatial scales. Fourier filtering (Roy et al. 2010) is a possibility for removing cirrus contamination of deep cosmological surveys that are primarily concerned with point sources (Eales et al. 2010), but for nearby galaxy groups and clusters (Davies et al. 2010) the size of the galaxies (of the order of 10 arcmin) compared to the cirrus (Fig. 1) makes this problematic.

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